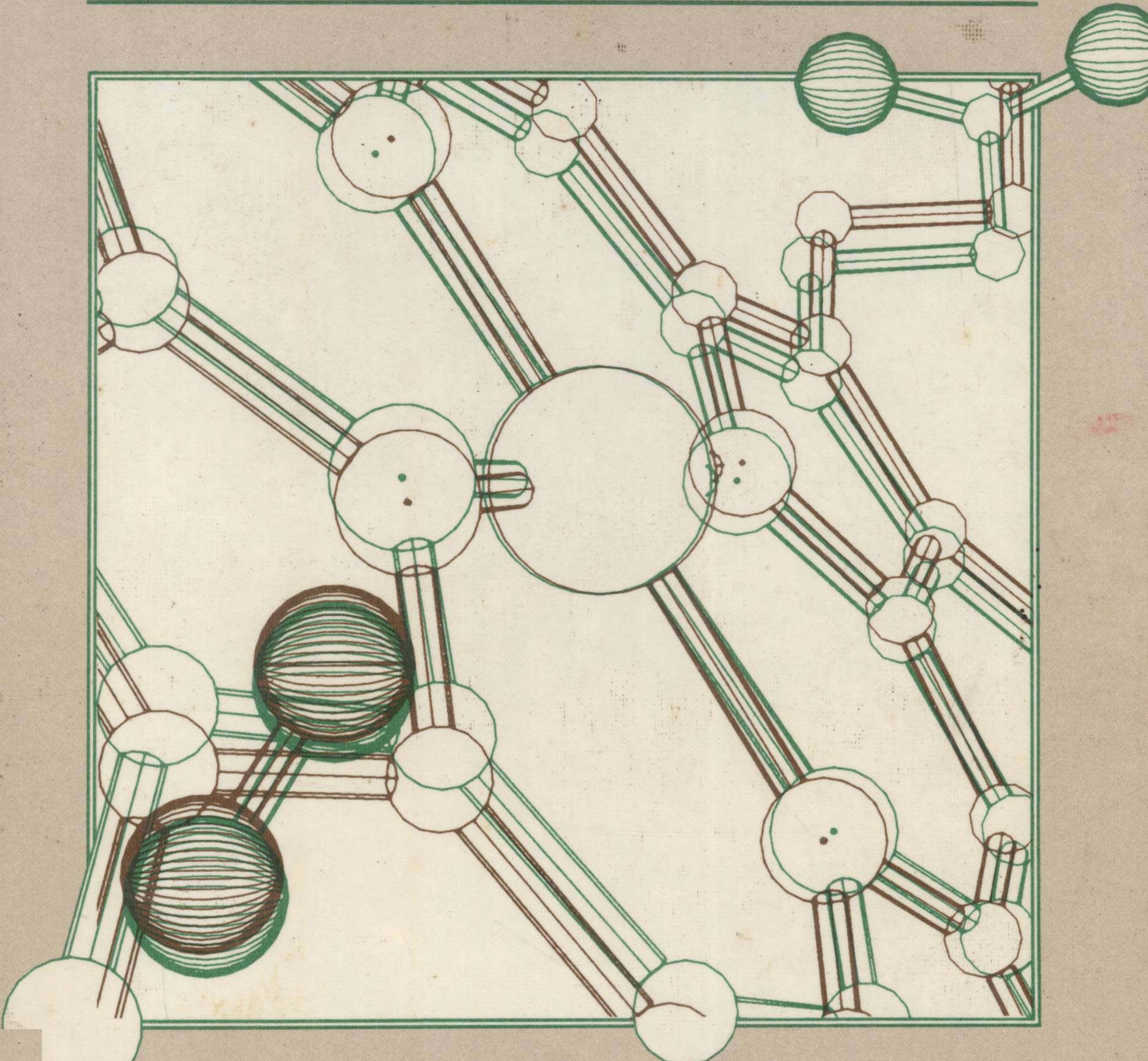
Audio-Visual Media for Education and Research – Volume 2

Computers for Imagemaking

Edited by **David R. Clark, Ph.D.** University of London Audio-Visual Centre



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A NOTE ON THE SERIES

The interests of the British Universities Film Council extend far more widely than its name would suggest and embrace every aspect of the use and production of audio-visual media and materials at degree-level. For many years the Council has been committed to specialist publication and launched the series **Audio-Visual Media for Education and Research** to fill a gap in the literature.

The aim of the series is to provide hand-books in defined subject areas in which the production and use of audio-visual media are discussed by teachers, researchers and producers. The emphasis is on producing a varied and informative introduction to the subject, rather than attempting exclusive presentation of advanced research results.

The first volume in the series was **Politics and the Media : Film and Television for the Political Scientist and Historian.** This second volume, **Computers for Imagemaking,** was inspired by a BUFC conference of the same name which Dr David Clark co-ordinated. All the contributions have been specially commissioned for the book.

The views expressed are, of course, those of individual authors, not of the Council.

Plans are in hand for future volumes in the series and further information about the series and about the work of the Council may be obtained from The Director, British Universities Film Council Ltd, 81 Dean Street, London W1V 6AA, England.

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Dr Yehonathan Hazony is head of the Interactive Computer Graphics Laboratory in the School of Engineering at Princeton University.

Dr John C. Gilbert works in the Graphics Section of the University of London Computer Centre. He has collaborated with John Richmond on developing graphics for the Open University mathematics courses.

Dr John Richmond is Executive Producer, Mathematics, at the BBC-Open University Production Centre and has commissioned a large amount of computer graphics for the OU courses.

Dr Kenneth C. Knowlton, one of the pioneers of computer animation, has worked for some years at Bell Laboratories, New Jersey, and has produced many computer-generated films which are widely used in education and research.

FOREWORD

This book sets out to tell the computer non-expert all he or she needs to know in order to begin Computer Imagemaking. In the hands of expert computer engineers, computer picture drawing systems have, since the earliest days of computing, produced interesting and useful images. Recently there have been major developments in computer technology; the consequence of these developments is that now it no longer takes the skill of an expert computer engineer to draw pictures; anyone can do it, provided they know how to make use of the appropriate machinery.

The field of computer imagemaking is wide. Until comparatively recently, the final product was always cinema film, whether for use in advertising, education or for artistic productions. Recent developments have, however, expanded the field to include television as a useful output device, and the arrival of such systems as Teletext and Prestel means that computer-generated images will feature more and more prominently in our everyday lives. Medical diagnostic techniques, such as the Brain and Body scanners, use analogue image display for the digitally computed images of sections through the body, and images of the earth taken from cameras on artificial satellites are becoming more accessible, especially for weather forecasting.

This book reflects the diversity of the field. The specially-commissioned articles cover not only the technological and cost factors but also some problems in the perception of images and their use in teaching and research.

The aim of the book is to provide the context for, and fundamental information on, the generation of images by computer. After reading it, the student, artist or film-maker should be ready to ask the right questions, express the project in appropriate terms and know where to go for facilities and advice.

ACKNOWLEDGEMENTS

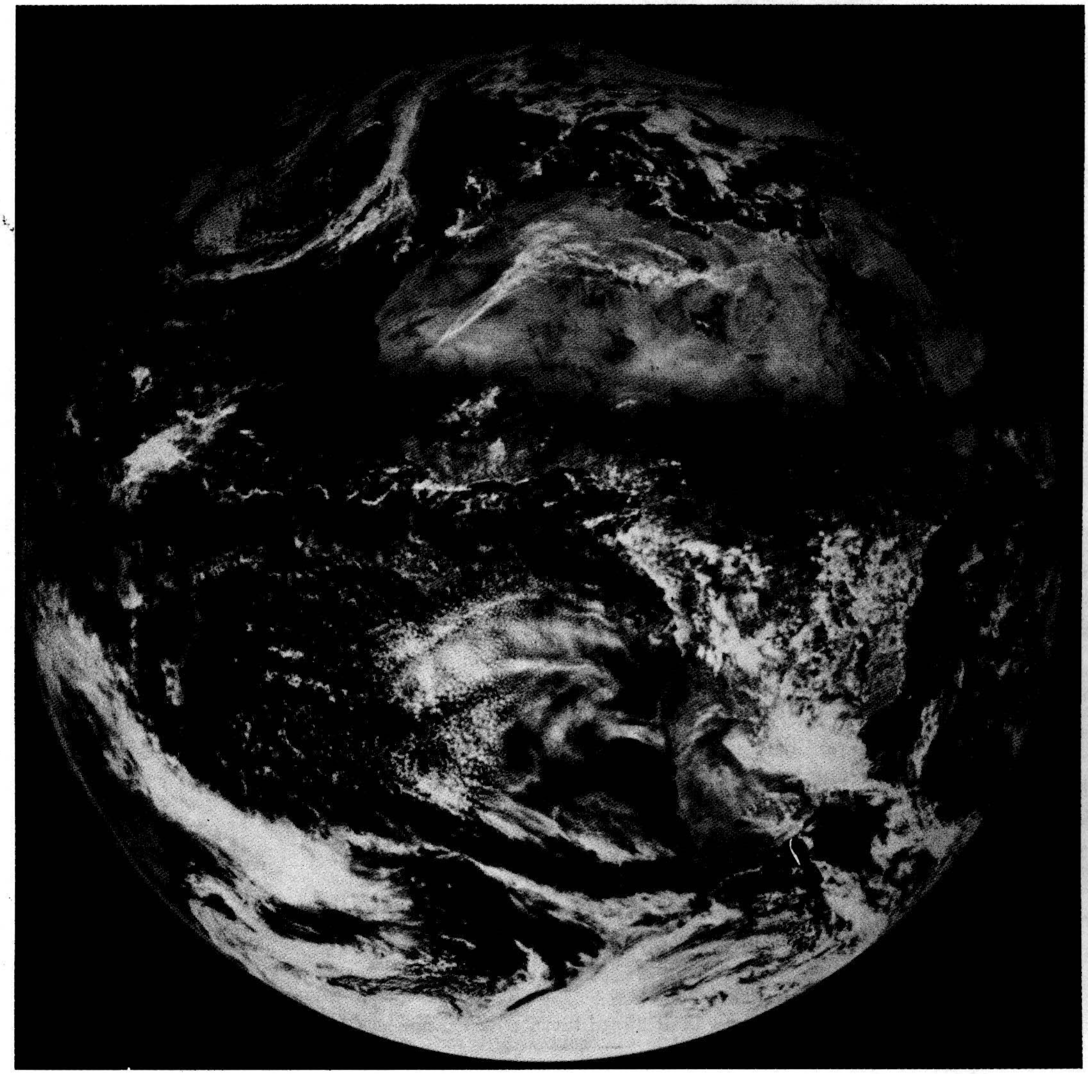
This book arose from the 1978 Annual Conference of the British Universities Film Council. The then Director, Yvonne Renouf, asked me to organise a strand of that conference to introduce non-specialists to the field of computer imagemaking. My introduction to the field came whilst teaching chemistry at The University of Toronto. Students in Professor J.C. Polanyi's group made a film in 1968 to show the dynamics of chemical reactions. Each frame was plotted on paper and photographed; it was a labour of love and there had to be a better way. At the University of London Audio-Visual Centre, the Director, Michael Clarke, has encouraged me to explore the field and I am grateful to him for that opportunity. My collaboration with Dr J.F.Wilson on the use of stereoscopic imaging for computed molecular structures has provided a practical opportunity for programming, and membership of the Interactive Planetary Image Processing System (IPIPS) team under Dr Garry Hunt at University College, London, has given me the chance to examine at first hand the latest developments in Image Processing.

The present Director of the British Universities Film Council, Elizabeth Oliver, oversaw the Conference and suggested that from it should come the second volume in the series **Audio-Visual Media for Education and Research**. As its Editor, I have the responsibility for the content, but the form of the book and its careful presentation are her work. I am very grateful to her for the time and attention she has given to its preparation for publication.

Nina McNeill composed the pages and accepted my many last-minute emendations with patience and understanding. I should also like to thank Paul Wilkes and Penny Hollow for their advice and expertise in the preparation of my diagrams for printing and also Penny Henry who typed my contributions.

Finally, I am indebted to the other contributors to this volume. Without their work, the field of computer imagemaking would be far less interesting than it is.

David R. Clark
May 1980



This picture, and the picture on page 28, are images of the earth from space. They were obtained from the METEOSAT satellite on **5 November 1978** at Noon GMT. This satellite is geostationary above 0° Lat, 0° Long. and sends three such pictures every thirty minutes. This is the image in the visible region of the spectrum. The earth being a globe, England, at between 55 and 60° North of the equator, is almost invisible, as well as being covered with clouds. Nevertheless images such as these are enormously useful for weather forecasting and climatology. At the Laboratory for Planetary Atmospheres, University College, London, Dr R. Saunders in Dr Garry Hunt's team is examining the most useful ways of treating such data using the IPIPS facility. Sequences of these images can be combined, after some processing to equalise the contrast ranges, to show the time-course of cloud development. A movie-loop of these images reveals both the global and local features of the weather in a most dramatic way.

Pictures of this kind are already the result of image processing. The signals representing the brightness of a point across the scanline of the imagemaking device in the satellite have been encoded, transmitted to a receiving station in Germany, re-assembled into an image and processed to remove any unwanted distortions incorporated by the camera system.

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THE TECHNICAL FOUNDATIONS OF COMPUTER IMAGEMAKING

David R. Clark
University of London Audio-Visual Centre

The recent history of computer imagemaking is, to a large extent, the history of the development of new technologies. The constraints which these technologies impose have determined both the style and process of computer imagemaking. A clear understanding of these factors, and an appreciation of the mechanisms of perception, are prerequisites for the study of picture making by computer. This chapter seeks to provide an introduction to the field.

The rate of appearance of new ideas in the various fields in which computers are used for imagemaking may just be beginning to decrease. The subject is beginning to stabilize. The preceding 20 years have witnessed an explosive growth in both the range and number of devices on which images can be created by computation. Whole classes of problems, like the hidden surface problem, were first posed, then solved, during this period, and there is now a recognised academic discipline called 'Computer Graphics', for want of a better title. As is always the case with a 'new' field of enquiry, it is the coming together of people with different backgrounds but a common interest that generates an explosion of creativity. No one person can claim the credit for starting the subject up; when the time is ripe, the process of nucleation seems to happen in several places almost simultaneously. There is no doubt, however, that the group formed by Ivan Sutherland at the University of Utah in the late 1960's has had a profound effect on the outlook of the field as we find it today. This is true of both the developments in machines for displaying images and for the strategies by which images may be most efficiently computed and ordered for plotting.

The decrease in the rate of decrease of computer memory cost, combined with the approach to the limit of switching speed of semiconductor junctions, makes it easier to predict the form that image display devices will take over the next twenty years. We are nearing the end of the innovation phase of computer imagemaking and are entering the period in which a large number of new applications for these imaging capabilities will be found and exploited.

THE VARIETY OF COMPUTED IMAGES

At this moment, computer generated images are already being used for a wide range of applications. For example, an expensive, but cost-effective, use is to simulate the views from the cockpit of an aircraft as the pilot 'flies' the aeroplane; it is cheaper to crash a simulator than a 747.

The movie industry in Hollywood has seen the potential for films produced entirely by machine, and no Sci-Fi feature is complete without its computer-animation-type pictures. The verisimilitude that is now attainable in computed images, if time and money are readily available, justifies the faith of the financial backers of the cinema; Edwin Catmull, in Ch. 4 sets out some of the problems in this area that are still to be overcome.

Simulation and movie-making are both attempts to generate images of 'real world' objects entirely mathematically. The camera has been replaced by a mathematical model. There is another field of computer imaging where the data is from some kind of camera, but the pictures have to be processed to be used. Two examples of this are the images from computer tomography – the 'brain scanner' and 'body scanner' images – and the pictures of Earth and Jupiter telemetered back from cameras aboard space craft.

These applications of computer imaging are often referred to as **Image processing**. The techniques that are used to display such images are no different from those used in simulators or movie-making; the main difference is that rather than being created to convey information, these images are examined and processed to extract the information that they contain. Here the major theoretical problems are in the fields of pattern recognition and artificial intelligence and novel picture-processing computers have been developed to speed the computations required.

A consideration of the problems of image analysis exposes one of the growth points for the next decade. The physiology of perception is just beginning to reveal the way that we construct mental images from the information impinging on the retina. An understanding of the way in which we see may suggest new and more efficient strategies for computing and presenting images.

Images, or pictures, can be thought of as at least 4-dimensional quantities. In addition to the two spatial dimensions of the image plane, an image has a temporal dimension. A 'still' picture is just a special case of this temporal sequence in which there is no change in the image from one instant to the next. A fourth dimension is the brightness, or intensity, of any point in the image at some instant. This brightness may be intrinsic to the object, or be a consequence of projecting a 3-space structure into the two dimensions of the image plane, or both. Extra dimensions are required to specify any colour that the image may have. A measure of the complexity of an image is the extent to which these dimensions can be portrayed. For example, adequate simulations of an emergency landing on an airfield known to the pilot require images that range over all the degrees of freedom. They must be large, change with time, and be good representations of the scene, both in terms of detail and colour. At the other end of the scale of complexity are the static, single intensity monochrome images to be seen on a Visual Display Unit, or, slightly more complex, the 'video games', whose images change (slightly) with time.

Between these two extremes lie the rest of the computer generated images. Images in which the degrees of freedom are considerably restricted tend to be called 'computer graphics'. These include the 'teletext' and 'viewdata' images, business graphics, the images of computer-assisted learning and the simpler examples of computer-aided design. There are no hard and fast divisions, but the limiting factors that delineate each group are almost always the limits imposed by the available technology.

There has never been a time when computers have not been used to produce images of some sort. Crude typographical images using a teleprinter, or dire renditions of the Mona Lisa from a line printer have always adorned computer room walls. They are on the one hand a tribute to the ingenuity of programmers and on the other a savage indictment of their artistic sensibilities. Nevertheless, the existence of such pictures is significant: there is an overwhelming urge to create images as a result of intellectual activity.

MODES OF DRAWING

There are two distinct modes that can be adopted for drawing images. These are now called the **Vector** and **Raster** systems. There have been several strands woven into the development of each mode. All the earliest systems, the teletype and the line-printer, were raster systems. This was because the writing head could only write in one direction across the paper and the paper could only be transported one way, up, past the head. The latest generation of machines are raster based, and this is to be the dominant technology for the rest of the century, but in that middle period of explosive development the only worthwhile device was the calligraphic, or vector plotter.

VECTOR SYSTEMS

The difference between the systems is not primarily one of technology. There is an important philosophical difference. A rasterised image has the property that the strategies used to encode, transmit and display it are in principle independent of the content of the image itself. On the other hand, a vectorised image is composed of only that information which is required to form the image. For example, it takes just as much time to transmit a television image of a completely blank screen as it does to transmit an image full to capacity with picture detail. The scanning raster must be completed in the same way in each case. The entire image is encoded in a form that bears no relation to what the image contains.

On the other hand, the instructions required to draw nothing on a vector device contain at the most a few orders to move on to the next image. At the other extreme of vector plotting, the more detailed the image, the more instructions there have to be in the plotting file.

These fundamental differences relate directly to the computational nature of the images. The logic of computing the image of a mathematical object is that the computation computes **something**. Some point or region of the object is transformed into some point or region in the image. A very large class of objects can be represented as a framework of straight lines. This fact is very useful because the projection of a straight line from the object into the plane of its image is also a straight line. Thus the computation of these objects can just become the computation of a number of lines. Since, until very recently, all computation has been by the serial processing of stored instructions, the output of an image computation is a string of information about the intersections of these lines. All the regions of the image plane that are not contributed to in this way by the image of the object are unspecified. This stream of data is ideally suited to vector drawing devices since they only draw lines. A raster device, on the other hand, must be instructed to draw 'nothing' on the raster path just as it must be instructed to draw 'something'.

The name **vector** for these plotting devices derives from the fact that a straight line is defined by its end-points. Since the end of one line is usually the start of the next, the commands to the plotter are always at least a pair of numbers representing the x and y values of the next endpoint. Mathematically, this pair is referred to as a vector, since it specifies a line of a given length in a given direction.

The list of all the vectors to be plotted is held in the plot file, and the organisation of this file so as to allow the updating of the picture with the minimum of effort is a very important part of the design of vector plotting systems.

Mechanical Plotters

The earliest vector-drawing machines were x-y paper plotters. Since they were designed to produce an ink-on-paper image, the time taken by the pen to reach a particular point from any point on the table was chosen with more regard to the positional accuracy to be achieved than to the total time required to draw an image. For still images, precision is more important than speed of drawing. We shall see later that this is not the case for images forming a sequence to convey the impression of motion.

As the need to draw larger numbers of images grew, mainly from the pressure from computer users wanting to make movie sequences, an alternative to photographing the paper plots one frame at a time had to be found. Looking back, it is remarkable that some of the pioneer computer film makers had the patience to photograph literally thousands of images one after the other.

The major factor controlling the speed of paper plotting was, and is, the mechanical movement of the pen. The pen was moved to its new position by motors controlled from analogue or, later, digital signals derived from the difference between the current [x,y] co-ordinates of the pen and the computer co-ordinates of the next point to be drawn. Since these calligraphic devices were designed to draw straight lines from the current to the next position, any attempt to portray a curve was limited by the extent to which the curve could satisfactorily be approximated by a number of short chords. The incremental nature of this style of plotting imposed a high level of mechanical precision on the device if the path traced out by a large number of line segments representing a circle, for example, was to close on itself accurately.

Light-emitting Plotters

An electron beam has effectively no inertia and so can be repositioned very fast. Used to excite a phosphor, as in an oscilloscope or TV tube, the path swept out by the electron beam could be made to leave a trail of light. There are three ways of making this trail 'permanent'.

Firstly, it can be used to expose photographic emulsion. This is the basis of the **Microfilm Recorder**. The film acts as the integrator to remove the decay-time of the phosphor. The point of light, tracing out the computed line segments for either seconds or hours, generates a final image in the film emulsion. This can be printed onto paper or projected onto a screen.

Secondly, the image can be frozen for a reasonable length of time onto the face of a special **storage tube**. This system has a large number of disadvantages that are set out in the chapter by DeFanti and Sandin but, because it was the only device available at the crucial time, it has formed the basis of a large number of systems and even today still has its adherents. This device was for display technology what FORTRAN was to the programmer – terrible for the job but (just) better than nothing. Only now are a generation of users coming up who are not blinkered by contact with either the storage tube or FORTRAN.

The third system of making this trail of light 'permanent' is to repeat the drawing of the image sufficiently fast to utilise the persistence of vision of the eye. This is the **Refreshed Display**. The physiology and psychology of the persistence of human vision is very complicated. The impression of 'flicker' depends on the size of the flickering image on the retina, whether it is in central or peripheral vision, whether it is coloured or monochrome, and on the relative contrasts both within the flickering image and between the image and its surroundings.

The most familiar devices that rely on the persistence of vision for their effect are the cinema and television. It is common knowledge that cinema film is projected at 24 frames per second. What is not so widely known is that this is not the rate at which the pictures are flashed on the screen. It is usual to flash every frame on and off three times; there is a three-bladed shutter spinning round in the light path once every 1/24th second, so the flicker rate is 72 images/second. The choice of 24 frames per second has more to do with the de-blurring of motion and the sensitivity of early film emulsions than with the persistence of vision effect under the viewing conditions found in a cinema.

These considerations have not been carefully applied to the repetitive drawing of the computed vector display image. A very fast vector drawing system might draw 5000 short vectors/second. Assuming a picture rate of 25/second, this might suggest that a picture composed of 200 vectors could be drawn sufficiently rapidly so as to appear not to flicker. There are two points here. Firstly, not a great deal can be drawn with 200 vectors. It might represent 20 circles each with 10 segments, a goodish approximation for circles whose diameter is less than 1/10 of the picture width. Secondly, at this rate, each point is refreshed every 1/25 second; moreover, its nearest neighbour is only refreshed at the same rate, so, unless the display subtends a small angle at the viewer's eye and is not highly contrasted with its surroundings, it may flicker objectionably. Real-time vector drawing is, then, rather restricted.

Brightness Variation in Vector Displays

The early electronic vector plotting devices were just simulations of the paper x-y plotters. They therefore carried over into the phosphorescent image system an unnecessary restriction. All parts of a line had to have the same intrinsic brightness. There are two ways to circumvent this limitation. The crudest is to draw over, or just beside, the previous line to make it brighter; the other method is to modulate the beam current during its passage along the vector. This last technique has practical limitations as well as requiring an alteration in the form of the data structure of the image. The deflection fields required to move the beam to its new position depend on the charge in the beam and rather complicated compensation circuitry is required to maintain high positional precision.

There is a practical variant of this second method. It is to vary the deflection **rate**. So long as the persistence of vision criteria are satisfied, slowing the traverse along the vector has the visual effect of brightening the line. However, this technique wastes valuable plotting time and serves only to reduce the total number of vectors that can be refreshed. These 'dwell time' techniques cannot work for storage tube displays. If the recording device is photographic film, rather than the eye, and there is no need to expose the film in less than 1/24 second, the technique of spending longer over lines that have to be brighter is a good one. In most modern microfilm plotters, where the vectors are constructed by brightening up dots on a very fine grid of points to form the line, the exposure is controlled by the number of times each individual point is flashed. An excellent survey of the various vector techniques that have been developed is to be found in Newman & Sproull, 2nd Edition 1979.

RASTER SYSTEMS

There are two strands woven into the development of raster display systems. The first is the desire to make use of the television system as a display device for computers. The second is that certain important calculations about an image, for example the determination of the visibility of surfaces in the 2-D projection of a 3-D object, are easier if the image plane can be treated as a raster. This discovery of the **scan-line algorithms** has swung the balance away from vector displays as the natural mode of display.

Video Rasters

Television is an example of a **raster refresh** display. In this case the persistence of vision has been taken carefully into account in the design of the display. Television images are presented at a similar picture rate to films. Their image rates are also similar but the way this is achieved is quite different. The picture rate for NTSC-standard television, found in those parts of the world over which England and Germany have no financial or political control, is 30 complete pictures per second. The rest of the civilised world receives 25 complete TV pictures per second. In both cases the complete **frame** is transmitted as two **interlaced fields**, so that the image rates are respectively 60 and 50 images per second. Since the pictures are transmitted a line at a time, starting at the top of the picture and working down, adjacent lines in the **frame** are drawn 1/50 second apart, although the time betweeen drawing every second line is 1/25 second. Since the scanning of the image on the face of the camera tube is done twice to cover the whole area, the interlaced field will be different from the first scan if any motion has taken place within the time it takes to scan one field. Thus, in general, unlike the 3 identical flashes of the cinema frame, the two 'flashes' of the TV fields may be slightly different. This helps to smooth motion but may give rise to inter-field flicker at 50Hz. This is easy to perceive at high contrast ratios in low ambient illumination and can be very trying to the eye.

The number of lines in the video raster varies from system to system. There are again two dominant standards:

NTSC	60 fields/sec;	262½ lines/field;	2 fields/frame.
PAL	50 fields/sec;	312½ lines/field;	2 fields/frame.

Both of these systems have an aspect ratio for the picture area of 4 x 3. The only useful correspondence between these two systems is that their respective line frequencies are almost identical. This fact has made the conversion of images in one type of system to the other possible, though very difficult.

The Frame Buffer

The price paid to secure the independence from picture content of the encoding system is very high. The data rate required to sustain a video raster is very large in comparison with the data rates within conventional computers. This is easy to see by considering the resolution obtainable from a PAL raster. The resolvable points must be represented by at least 1 digital bit of data.

The PAL raster contains 625 lines in a complete field but not all of these contain picture information. Some 22 lines at the start of each field and about 3 at the end are within the **field blanking** period of 25 lines. Thus in the complete raster only 575 lines are used to contain picture information. Since the aspect ratio of this picture area is 4 x 3, each line must be composed of 768 points if horizontal and vertical definition are to be the same. This gives the total number of resolvable points, as, in in theory, 441600.

Digital data representing the intensity values of each of these points must be supplied every 1/25 second. However, this data must be supplied at the right moment in the raster and the true data rate is calculated by noting that 768 pieces of information must arrive during the drawing of one line. To allow for the electron beam to be re-positioned at the start of the next line after completing the previous scan, a **line blanking** period of 12μs is allowed in the total line period of 64μs. Thus the data rate of a PAL TV line that has identical horizontal and vertical resolution is 768 points in 52μs, i.e. 14.77 million point values/sec. This is 1.85 Mby/sec if each point can be either 'on' or 'off' and these bits are packed into 8-bit bytes. Although just possible on very powerful computers, such data rates impose a great strain, all for a very poor picture.

The corresponding figures for the NTSC system are a 'raster' of 480 x 640 = 307200 points and a 1-bit point rate of 1.54 Mby/sec.

The only way to bridge the gap between the rates of computation and display is to construct a **frame buffer**. This is easiest to imagine as a piece of fixed store (originally a spinning disc) that is continually being read as a raster at video rates whilst independently being written to at a much slower pace and in the order most suited to the computation in hand. Thus, as the buffer gradually fills with the picture information, the picture displayed at video rates appears to develop in the sequence in which the picture elements, or **pixels** are loaded.